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14. ABSTRACT
The interaction between tides and topography, and mixing which can result, have been examined through nonhydrostatic numerical simulation, and compared with theoretical predictions, and data from observations. Important results are (a) the generation of small-scale shears when internal tides reflect from topographic corrugations; (b) the breaking of internal waves at slopes near the critical angle, for slopes of a wide variety of shapes.

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Mixing by Tidal Interaction with Sloping Boundaries

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LONG-TERM GOALS

The long-term goals of this project are to obtain an understanding of the mechanisms by which tidal energy is used to vertically mix the ocean against the action of gravity. Ultimately better parameterizations of the mixing caused by tides will result, allowing better prediction of coastal dynamics, biogeochemistry and sediment transport and the oceanic general circulation.

OBJECTIVES

The process of mixing by tides interacting with topography involves several stages. First some fraction of the energy contained in the barotropic tide must be converted into baroclinic energy, through the generation of internal tides and turbulent boundary layers. Secondly, the energy in the internal tides must be transmitted into smaller vertical wavelengths, thereby increasing the vertical shear of the motion. When vertical shears are sufficiently strong, instability may result, leading to overturning and mixing. Finally, the mixed fluid is transported away from the mixing region modifying the ocean stratification. The net effect of the tides on the ocean stratification depends on the efficiency of all three processes.

Our objectives are to understand (a) the generation of internal tides by the interaction between barotropic tides and topography including finite-amplitude three-dimensional variations in topography, finite-amplitude barotropic tidal forcing, non-hydrostatic effects and the boundary layer processes; (b) the mixing generated by internal tides reflecting from a sloping boundary in the presence of both two- and three-dimensional variations in slope, and finite rotation; and (c) the mechanisms of lateral and isopycnal transport of mixed fluid away from the boundary induced by the secondary circulations generated through spatial variations in mixing. Earlier studies have ignored three-dimensional large amplitude variations in topography and non-hydrostatic effects (which are important for small-aspect ratio motion).

APPROACH

We use high-resolution numerical simulations to explicitly resolve the turbulent mixing processes. For such simulations we require a numerical model which can (a) capture the non-hydrostatic physics of overturning and mixing processes and (b) include arbitrary three-dimensional variations in topography. The Marshall et al. (1997a,b) code (known as the MIT ocean model), which is non-hydrostatic, and includes topography through a finite-volume formulation, is such a model. We are carrying out three different groups of simulations: (a) We impose topography, barotropic tides and subinertial flows suggested by recent observations (e.g. the region of the TWIST field program, Polzin et al, 1998 and Monterey Canyon region, Petruncio et al., 1998), and investigate the internal tide generated by the flow-topography interactions, comparing these results with earlier models which assume small-amplitude (e.g. Bell, 1975) or two-dimensional finite amplitude (Baines 1982) topography. (b) We impose internal tide forcing and investigate the interaction with a two-dimensionally varying slope, focusing on the influence of finite rotation on the overturning and mixing, and the effect of slope variations in localizing mixing, comparing with earlier laboratory and numerical studies with uniform slope and no rotation (Ivey and Nokes, 1989; Slinn and Riley, 1996). (c) We examine reflection of internal tides from three-dimensionally varying topography.

TASKS COMPLETED

A study of the internal tides generated in the TWIST region was completed, and results are documented in two manuscripts submitted to Journal of Physical Oceanography (Legg, 2003a; Legg 2003b). In this study data from the LIWI funded TWIST project (Kurt Polzin, PI) was used to initialize the stratification and topography for a region of the East Coast. The model was forced with either the cross-slope barotropic tidal signal (imposed at the off-shore open boundary) or with the along-slope barotropic tidal signal (imposed through a body forcing term). The generation of internal tides at the shelf-break, and over the corrugations on the slope was simulated, and the scattering of the shelf-break waves from the corrugations examined. In order to help interpret the results, the theory of Thorpe (2001) was extended to include rotation, necessary to describe the scattering of the shelf-break internal tide from corrugations.

A study of internal wave breaking at variable topographic slopes was completed, and results are documented in a manuscript submitted to Journal of Physical Oceanography (Legg and Adcroft, 2003). In this study internal waves were forced at an offshore boundary and allowed to propagate toward a continental slope. Calculations were carried out in 2-dimensions for a variety of topographic shapes (concave, convex, planar). An investigation of the sensitivity to model viscosity and the nonhydrostatic physics was included. A wave Froude number criterion was developed to predict the range of slopes over which the nternal waves would break.

RESULTS

In simulations with TWIST topography and stratification an internal tide is generated at the shelf-break by the cross-slope barotropic tide. This internal tide reflects from the slope in a region of corrugations; in addition the reflected wave scattered waves are generated with an along-slope wavenumber given by the wavenumber of the corrugations. These scattered waves are not present if planetary rotation is ignored, and result from the flow of the along-slope velocity component of the primary internal tide (zero in the absence of rotation) over the corrugations. The scattered waves can be predicted by extending the theory of Thorpe (2001) to include rotation, and there is qualitative agreement between the forms of the predicted velocity profiles and the simulated velocity profiles, in addition to the observed velocity profiles. Hence wave scattering at corrugated topography is a mechanism for scattering low mode internal wave energy into higher vertical modes, generating greater shear and greater potential for mixing.

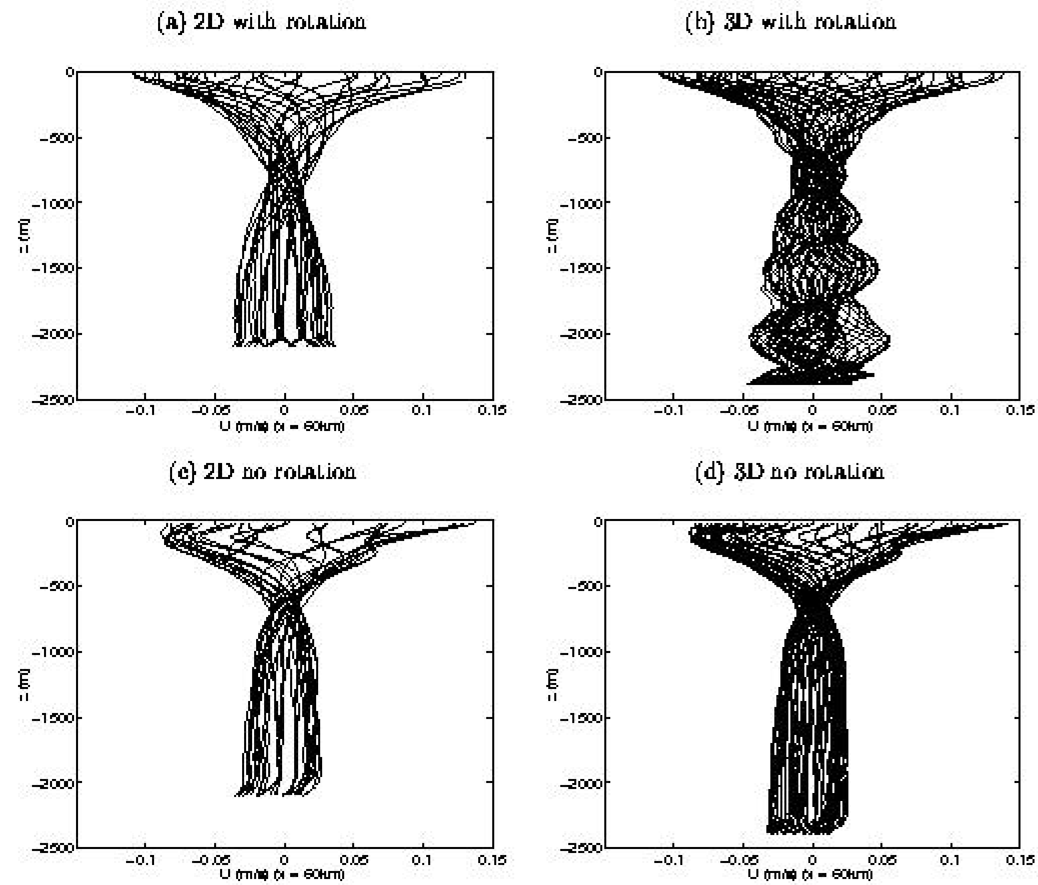

Figure 1: Vertical profiles of cross-slope baroclinic velocity at a location on the continental slope for several tidal cycles, shown for several different simulations: (a) 2D calculation with rotation, (b) 3D calculation with rotation, including topographic corrugations of wavelength 3.3km, orientated up and down the slope, (c) 2D calculation without rotation (d) 3D calculation without rotation, including corrugations. When both rotation and corrugations are included, much more small-scale structure is seen in the velocity field, leading to greater shear especially at depth.

2. Mixing generated by internal tide reflection at concave and convex slopes

Our numerical calculations have examined the reflection of an internal wave from continental slope topographies which are planar, concave or convex. Whereas earlier analytical studies predict that concave slopes near the critical angle will lead to less mixing than planar or convex slopes, we find strong mixing in all cases, in the form of bores propagating up the slope, as well as shear instability behind. In all cases a region of mixed fluid results bounded below by the topography, and above by the wave characteristic We conclude that the principal difference between our calculations and the earlier studies is the nonlinearity of the flow. The bores result when the Froude number (flow speed / wave phase velocity) of the reflected wave exceeds unity - the reflection process tends to increase the velocity amplitude and decrease the group velocity of the wave. We derive a range of slope angles around the critical angle at which internal tide breaking can occur, and our predictions agree well with our numerical results.

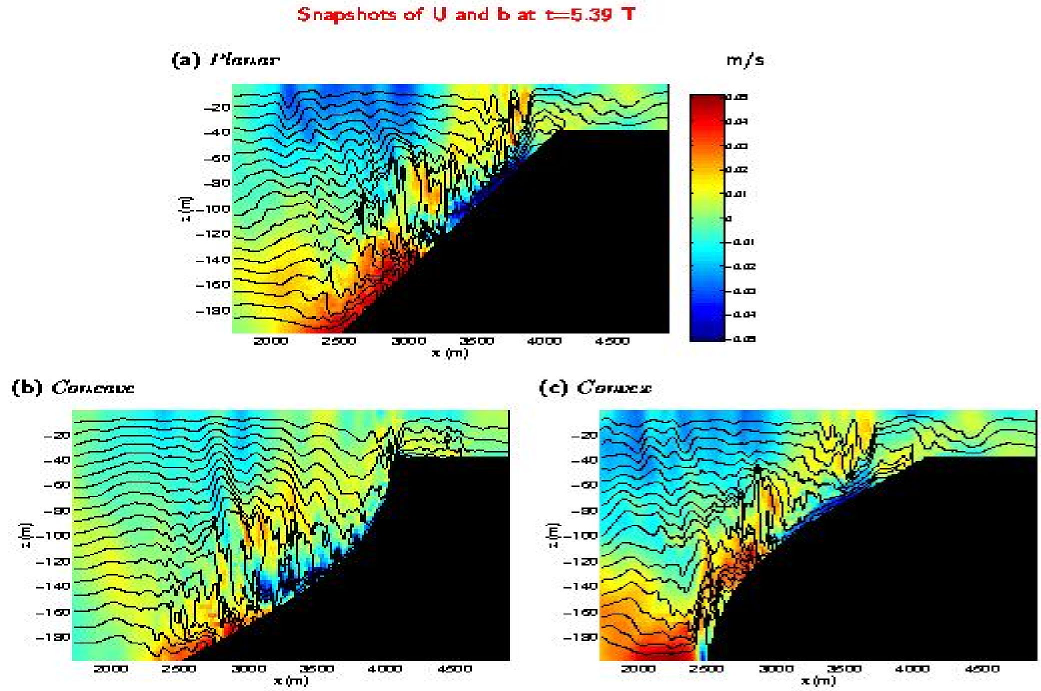

Figure 2: Snapshots of cross-shelf velocity (color) and isopycnals, from 3 different simulations of a mode 1 internal wave reflecting from a sloping boundary. In all three cases the average slope is at the critical angle for the incident internal wave, but the slope shape is (a) planar, (b) concave, (c) and convex about the mid-depth critical point. Whereas analytical theory predicts enhanced mixing due to critical angle reflection only for planar and convex slopes, all three simulations show turbulent mixing, caused by an internal bore propagating up the slope. The bore is characterized by sharp horizontal density gradients, and local overturning.

IMPACT FOR SCIENCE

Our results are helping in the interpretation of observations of tidally forced flows on the continental slope observed by LIWI investigators and others. Our results are demonstrating mechanisms for exciting small vertical scale baroclinic response to barotropic flow over topography. These small vertical scales (and hence large shears) are essential if the tidal forcing is to generate mixing, as widely speculated in recent years. Ultimately these results may help to improve parameterizations of tidal mixing over topography for inclusion in global and coastal circulation models.

RELATIONSHIP TO OTHER PROGRAMS

This project examines processes closely related to observations included in LIWI (Polzin, Toole and Schmitt and Paduan, Rosenfeld, Kunze and Gregg). We have been actively communicating results with K. Polzin, E. Kunze, J. Nash, R. Street and R-C Lien to help interpret observations made during LIWI and compare with other numerical simulations of these phenomena.

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Legg, S. 2003a: Internal tide generation on corrugated sloping topography: Part 1: Cross-slope barotropic forcing. Submitted to *J. Phys. Oceanogr.*

Legg, S. 2003b: Internal tide generation on corrugated sloping topography: Part 2: Along-slope barotropic forcing. Submitted to *J. Phys. Oceanogr.*

Legg, S. and A. Adcroft, 2003: Internal wave breaking at concave and convex continental slopes. Submitted *to J. Phys. Oceanogr.*